Observation of weak magnetic fields around galaxies with LOFAR

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The origin of cosmic magnetism
and its role for
galaxy formation
and
galaxy evolution
is still unknown

The four tools of radio synchrotron emission

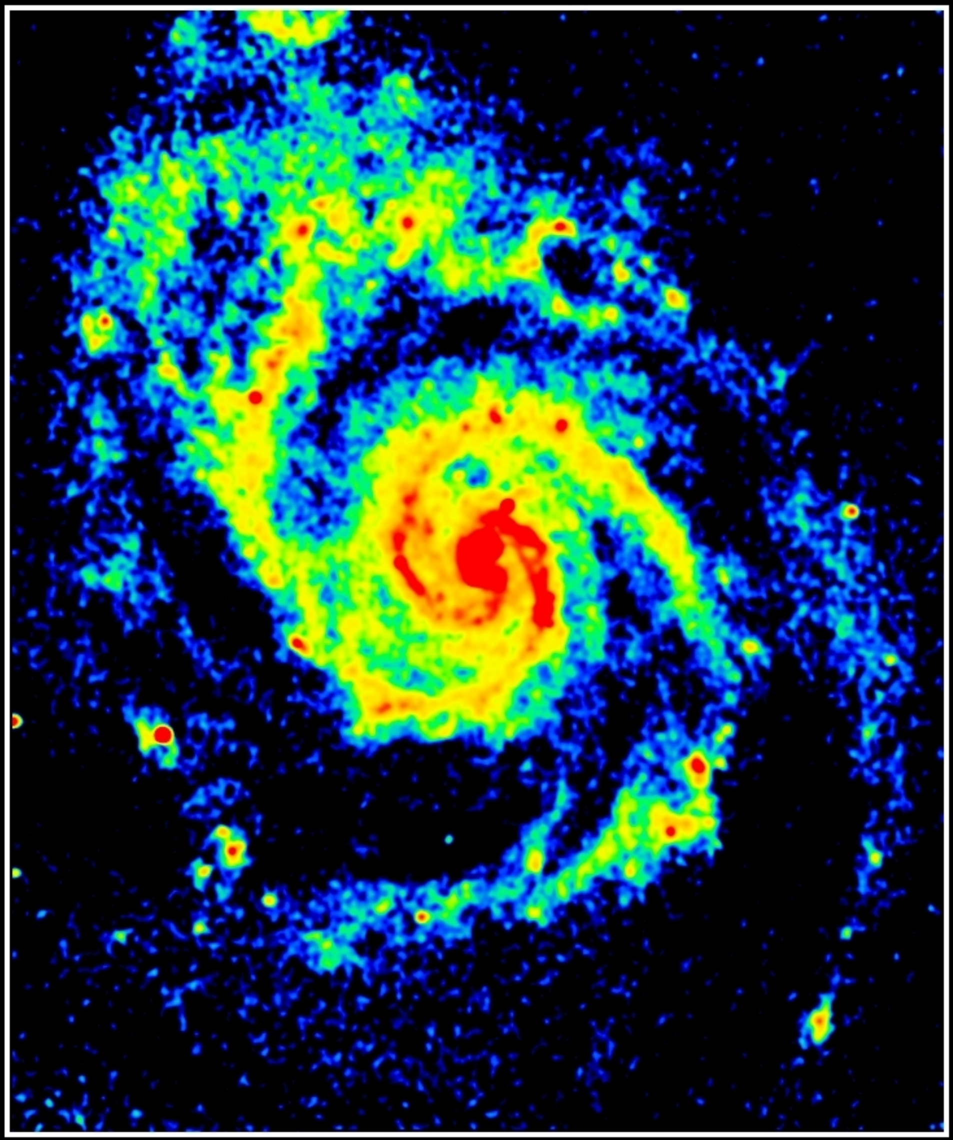
- Total intensity:
  Distribution and strength of total magnetic fields

- Polarized intensity:
  Distribution, strength and orientation of anisotropic or regular magnetic fields

- Faraday rotation:
  Sign of regular fields

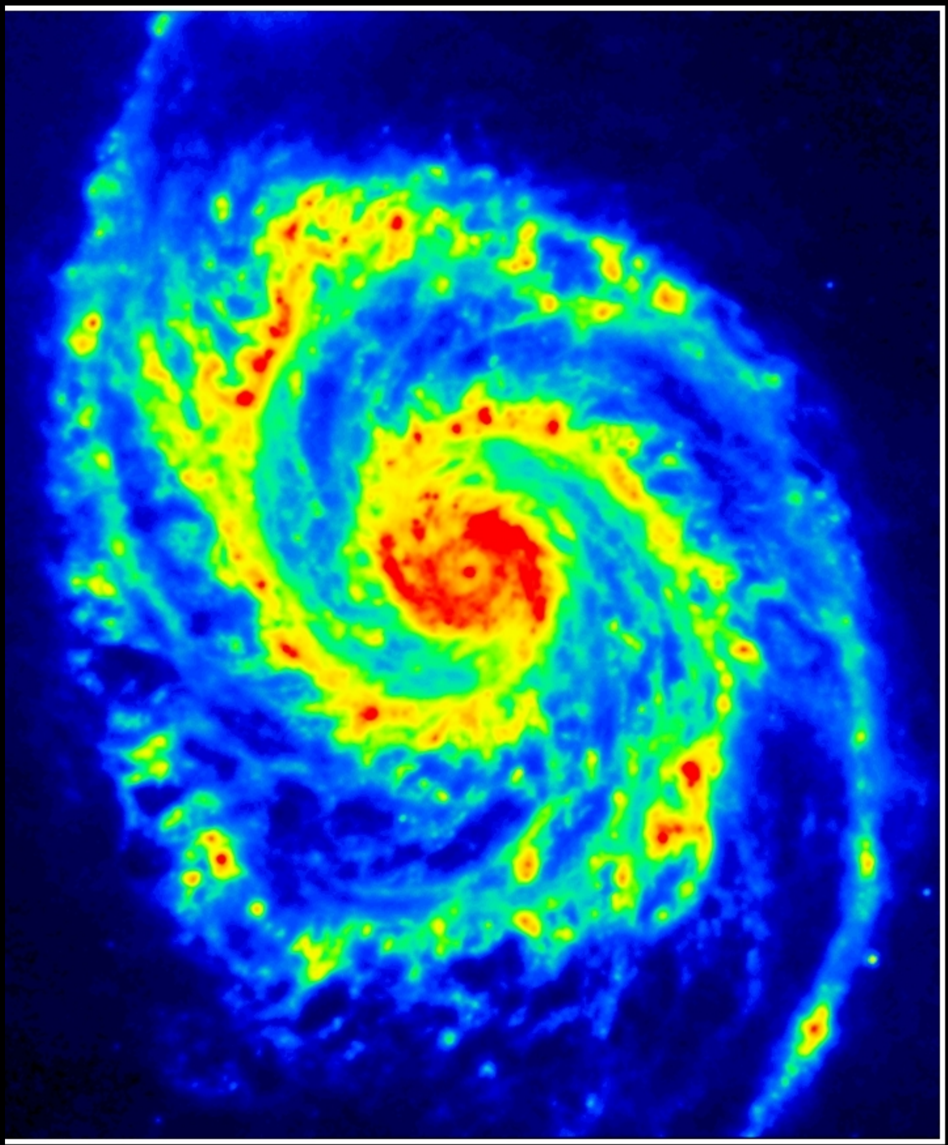
- Faraday depolarization:
  Strength and scale of turbulent fields

Radio continuum
(Effelsberg + VLA 6cm)

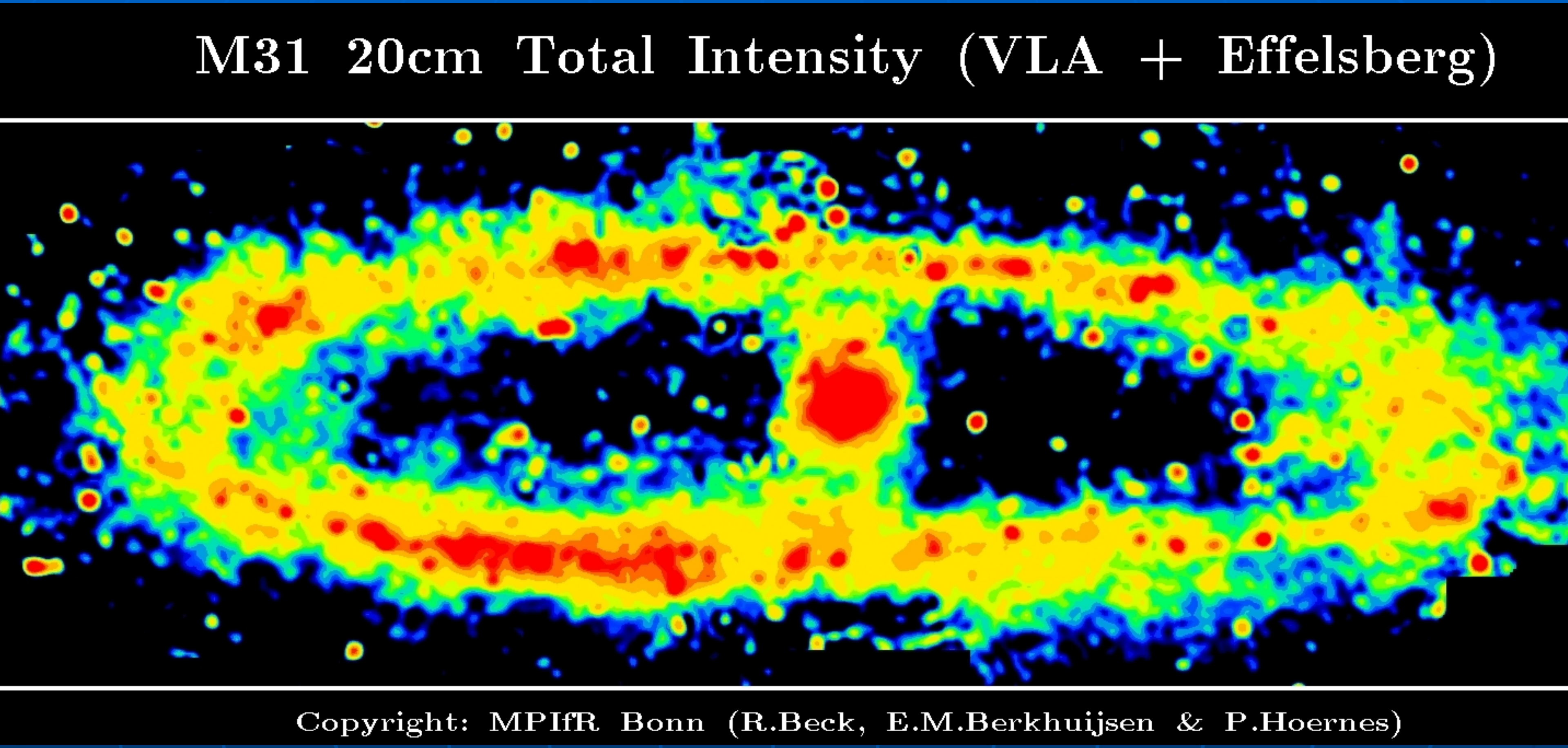


Fletcher et al. 2007

Infrared
(Spitzer 8μm)



Schinnerer et al. 2006



Cosmic-ray electrons are confined to the bright ring, but the synchrotron-weak inner regions may still contain magnetic fields

- High-frequency synchrotron, radio thermal and infrared emission are closely related
- High-frequency synchrotron emission shows magnetic fields and young cosmic ray electrons around star-forming regions
- The observation of high-frequency synchrotron emission away from star-forming regions is limited by the propagation within the lifetime of cosmic-ray electrons

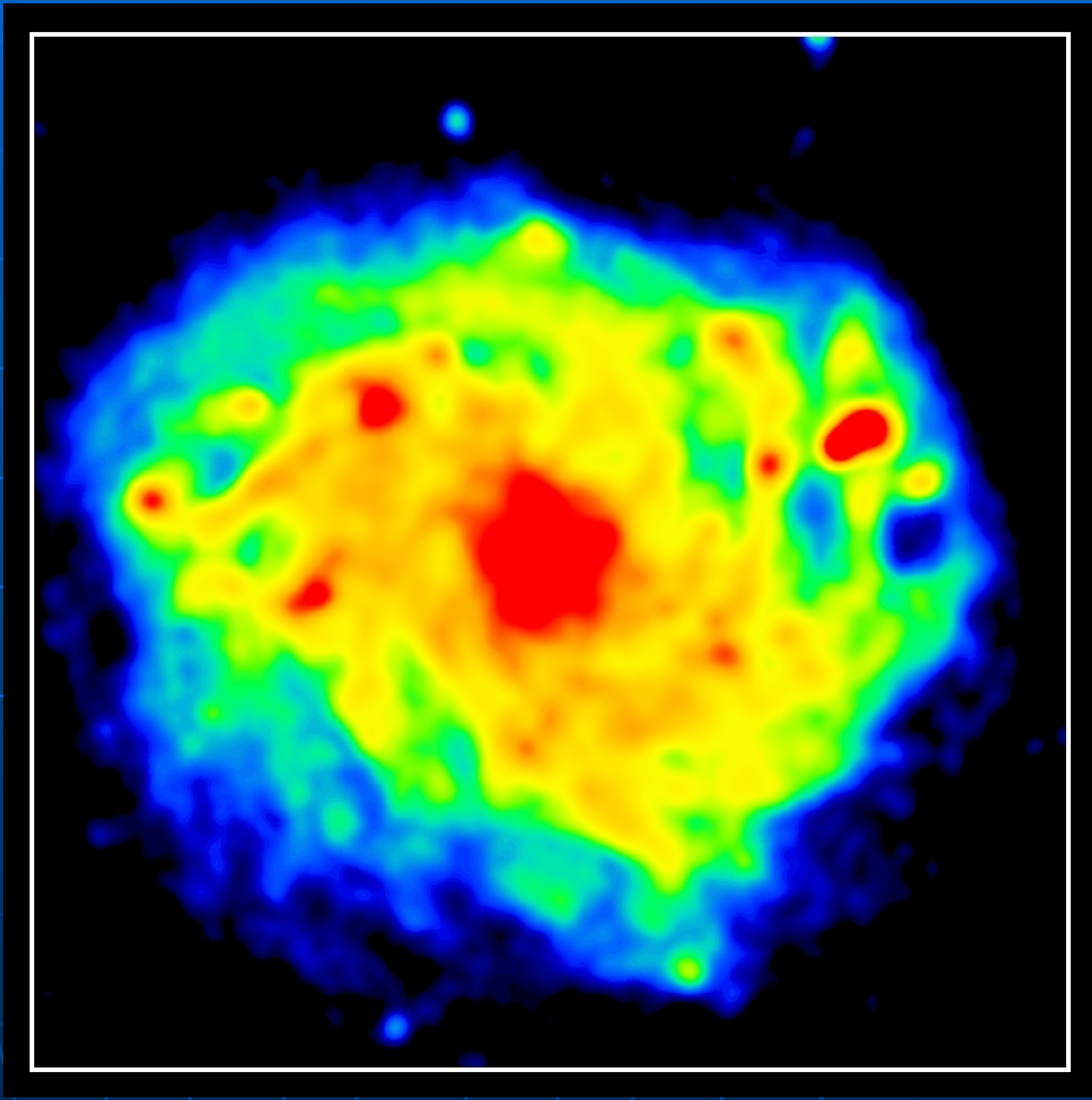
Open questions

- How extended are galactic magnetic fields ?
- Are they strong enough to affect the dynamics in outer galaxies (halos, winds, interactions, general rotation) ?
- What can they tell us about the history of a galaxy ?
- Are they connected to intergalactic space ?
- What is their origin (primordial, dynamo, MRI) ?

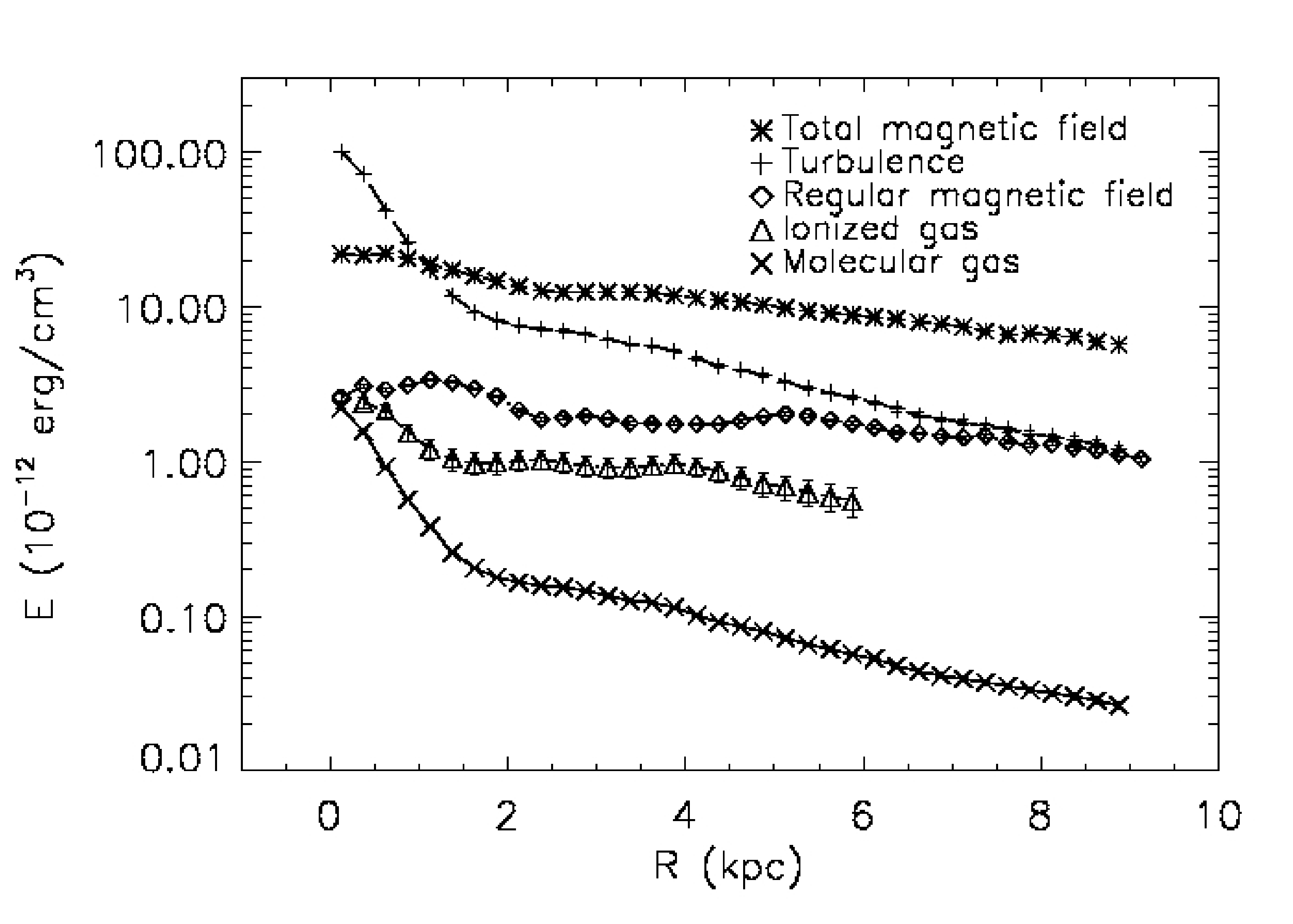
NGC 6946

20cm Total synchrotron

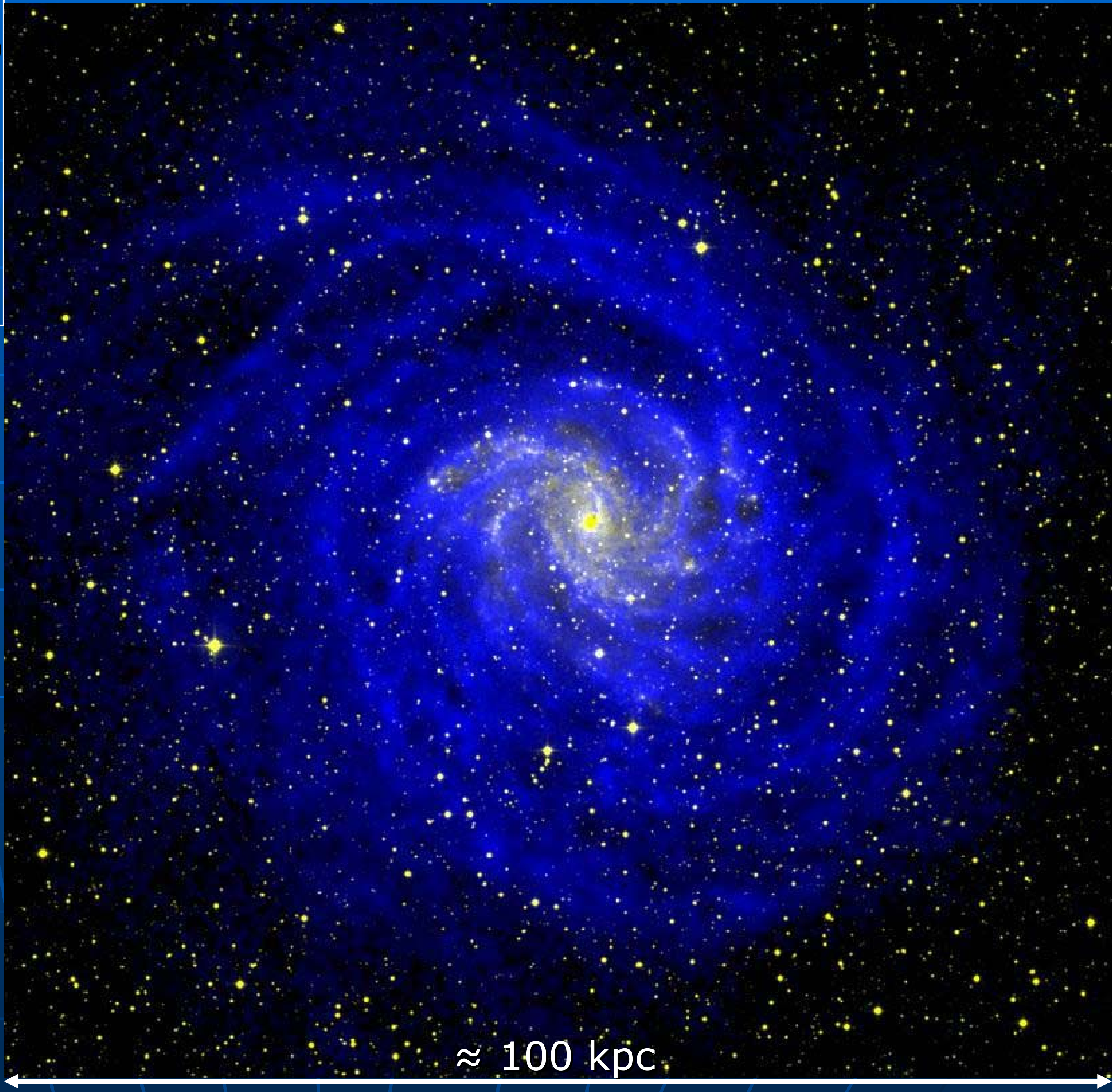
(Beck 2006)



Energy densities in NGC6946



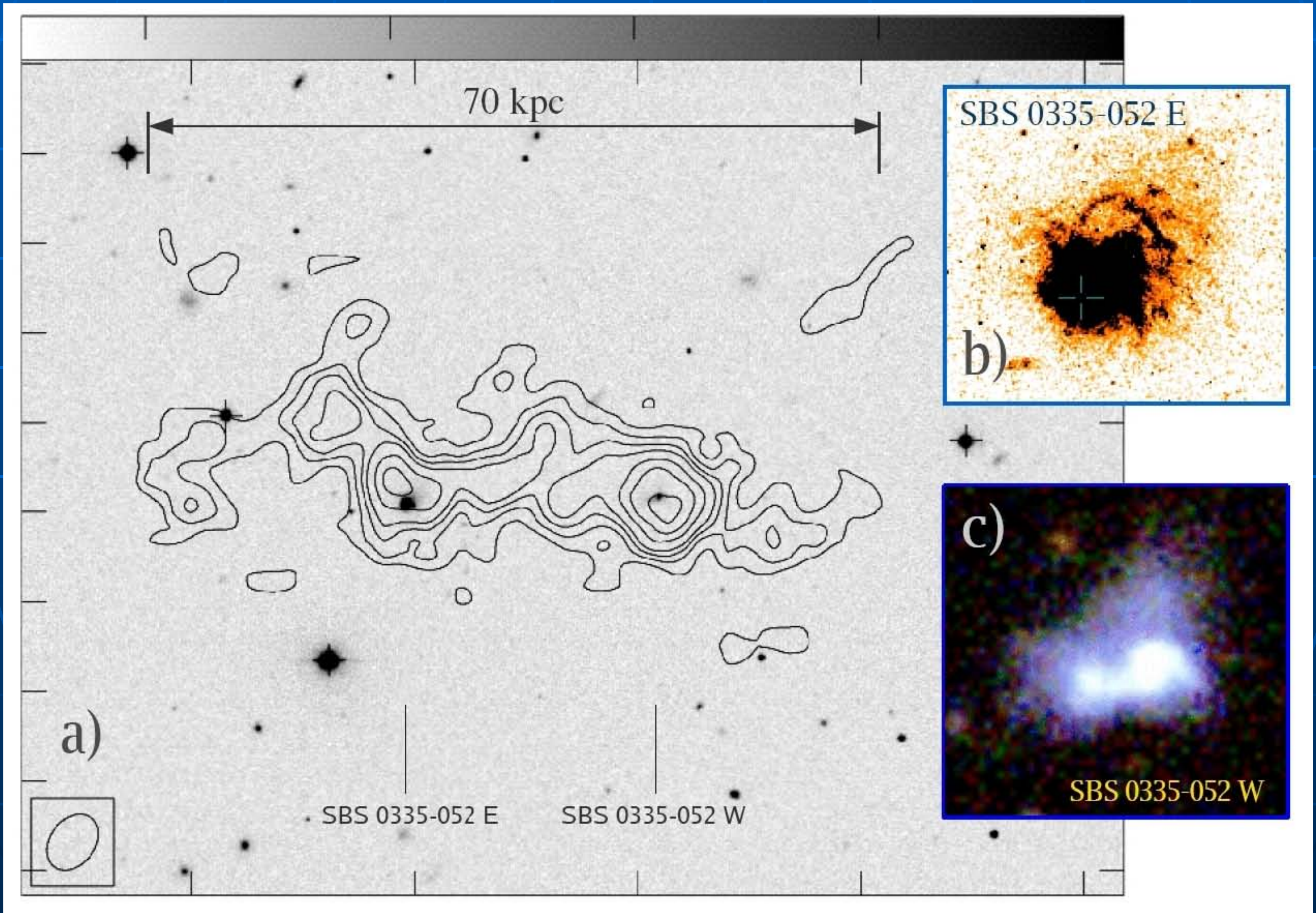
NGC 6946
WSRT HI
+ optical
(Boomsma et al.)



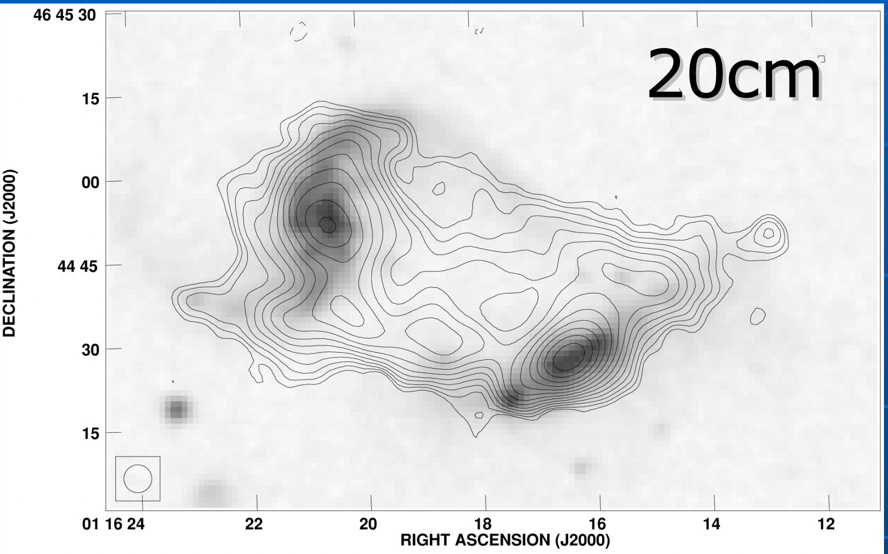
HI filament
+ dwarf galaxies

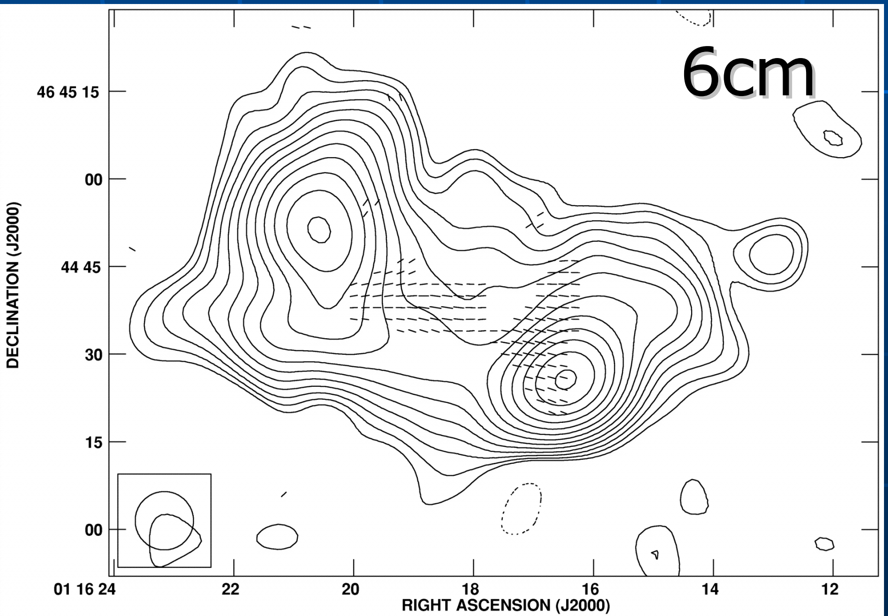
(Papaderos 2007)

(see talk by Polychronis)



"Taffy" galaxies UGC 12914/5





Condon et al. 2002

- ≈10μG field strength in the bridge, weak polarization
- magnetic field dominates the gas flow
- low radio-farinfrared ratio
- needs "direct hit" interaction
- occurs for ≈1% of the galaxies in the local Universe
- unique diagnostics for major galaxy mergers

LOFAR:

Observing *old* cosmic-ray electrons in *weak* magnetic fields

- Frequency of synchrotron emission: $\upsilon \sim E^2 B_\perp$

  Observing at low frequencies traces electrons with low energy ***E*** and/or in weak magnetic fields ***B***

- Electron lifetime ***t*** against synchrotron losses:

  $$t \sim E^{-1} B_\perp^{-2} \sim \upsilon^{-0.5} B_\perp^{-1.5}$$

  υ=50 MHz, $B_\perp$=10µG: E=0.6 GeV → t ≈ 1.5 10^8

  Observing at low frequencies traces **old** electrons

-

Propagation lengths of cosmic-ray electrons

- Propagation with Alfvén speed in halos (10^{-3} cm^{-3}):
  v ≈ 70 km/s · B (μG)

- B > 3.25 $(z+1)^2$ μG: Synchrotron loss dominates
  Propagation length of electrons emitting at 50 MHz:
  $L \approx 330$ kpc / ($B_\perp$ (μG))$^{0.5}$

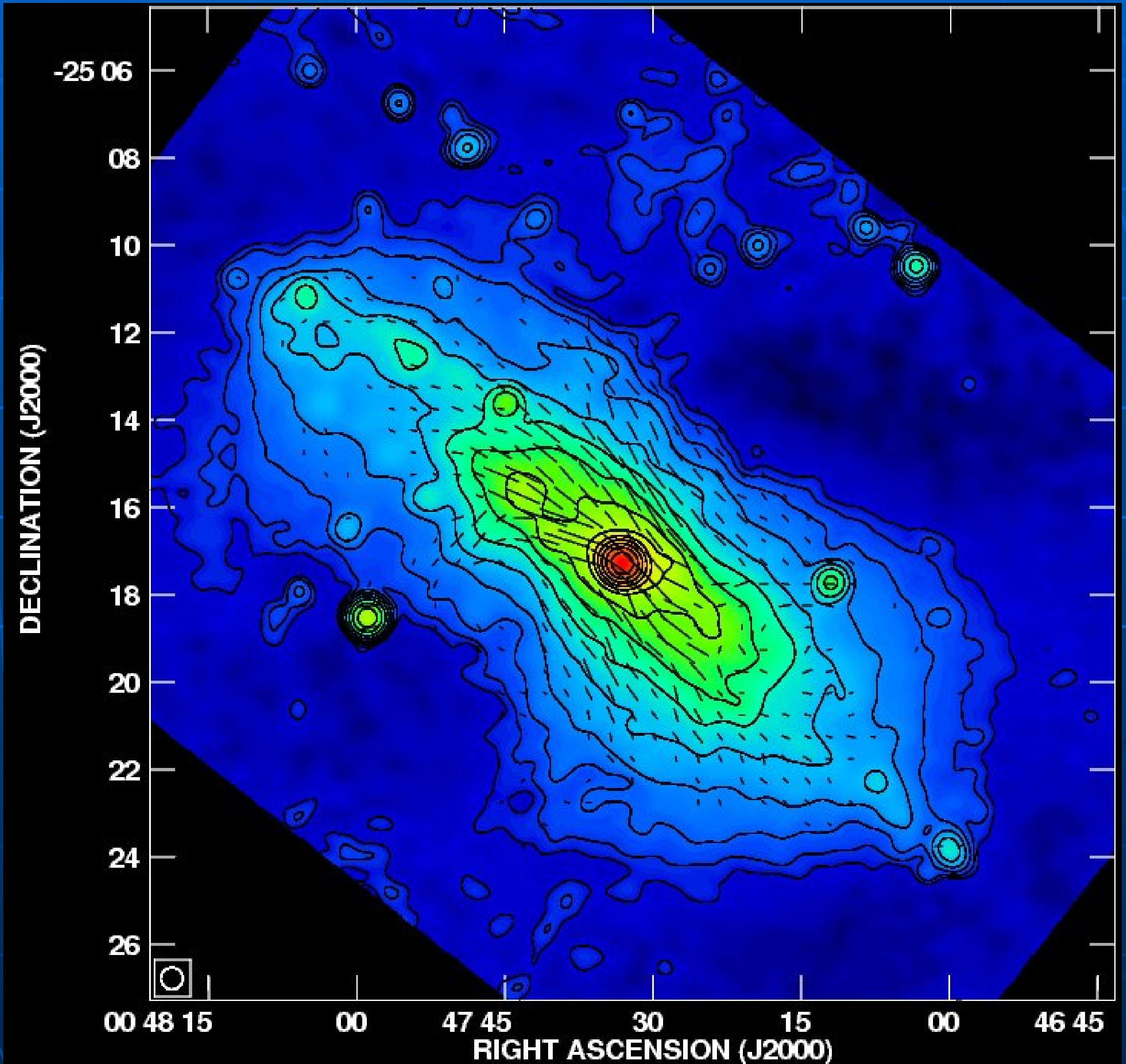
- B < 3.25 $(z+1)^2$ μG: Inverse Compton loss dominates
  Propagation length of electrons emitting at 50 MHz:
  $L \approx 30$ kpc ($B_\perp$ (μG))$^{1.5}$

- Maximum propagation length: ≈ 200 kpc

NGC 253

(PhD Heesen)

VLA+Effelsberg 6cm



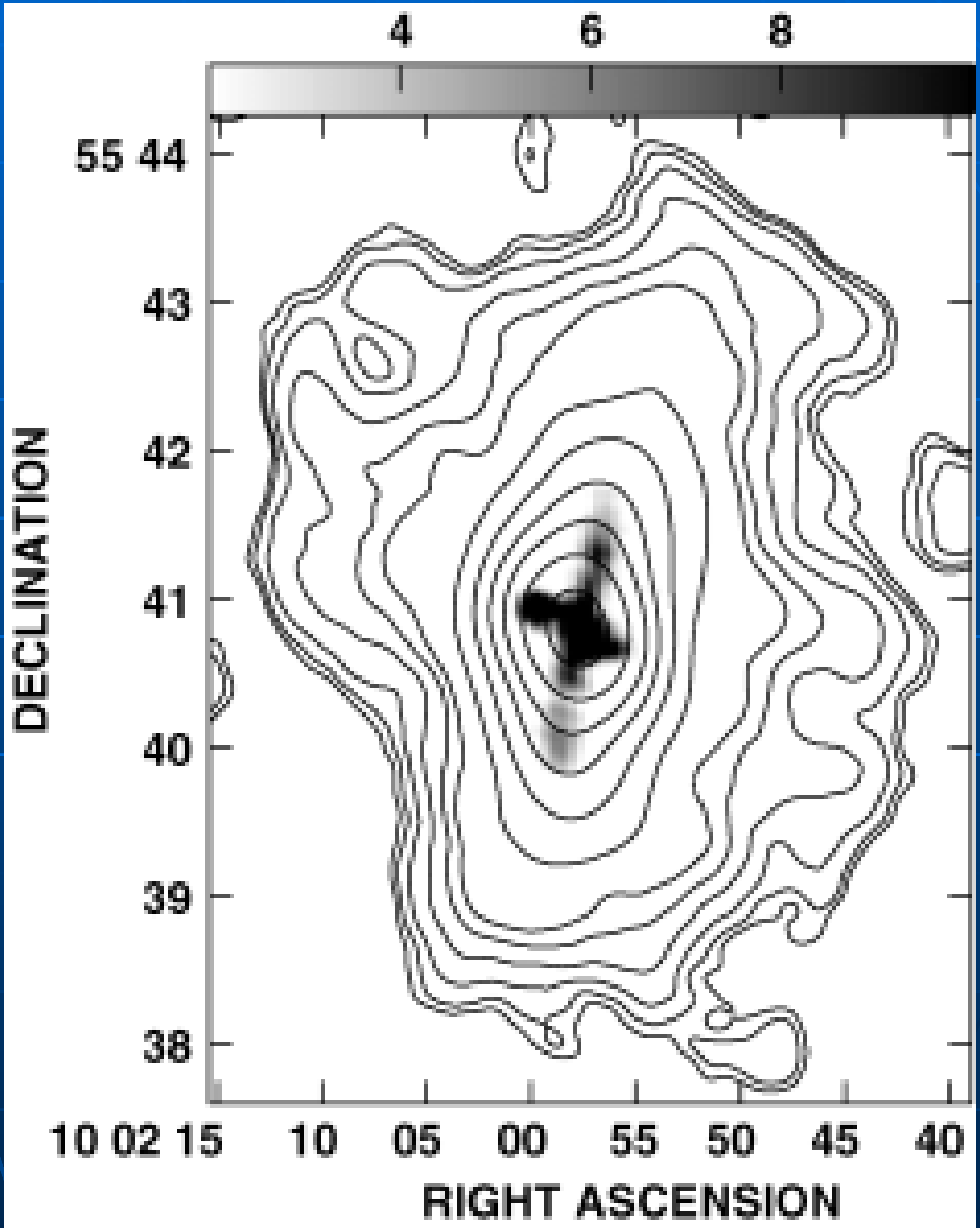
Halo extent limited by synchrotron losses

NGC 3079

GMRT

615 MHz

(Irwin & Saikia 2003)

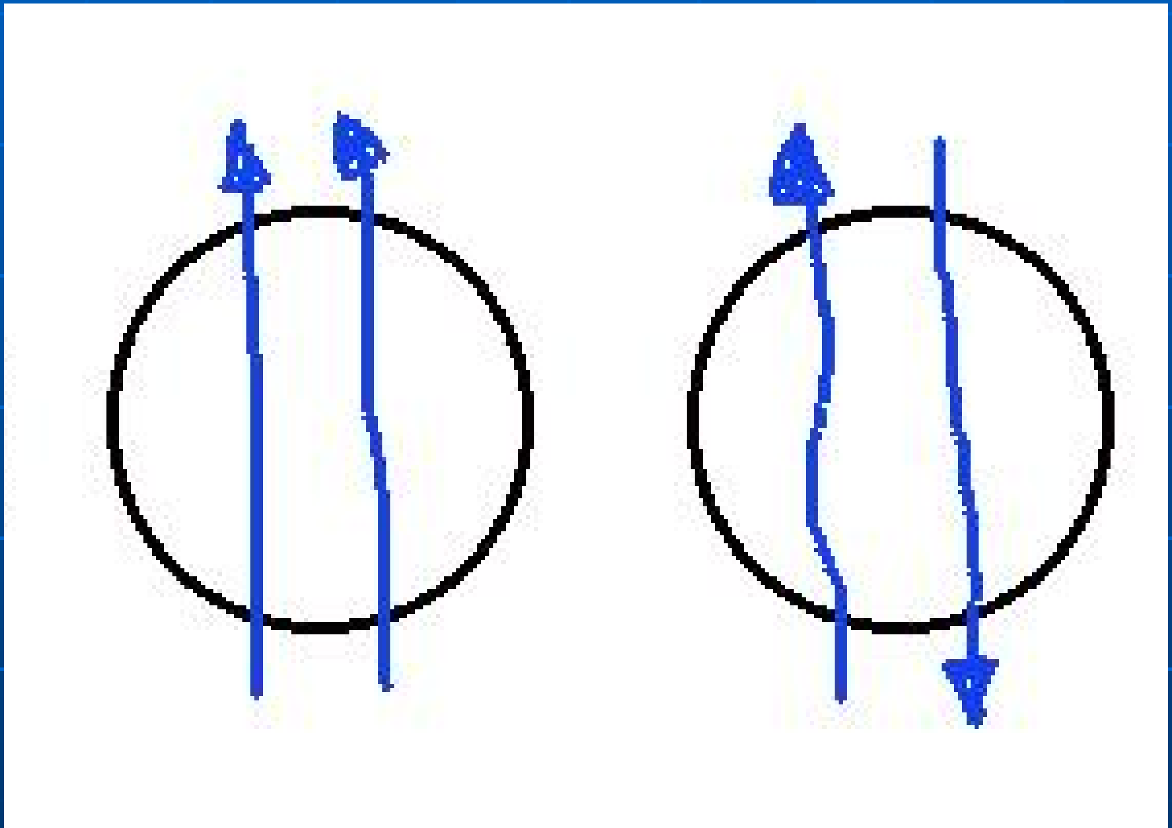


Radio polarization
traces regular or anisotropic magnetic fields in the sky plane

- Regular magnetic fields are generated by dynamo action
- Anisotropic magnetic fields are generated by compressing or shearing gas flows

Polarization traces non-uniform gas flows

Magnetic field components



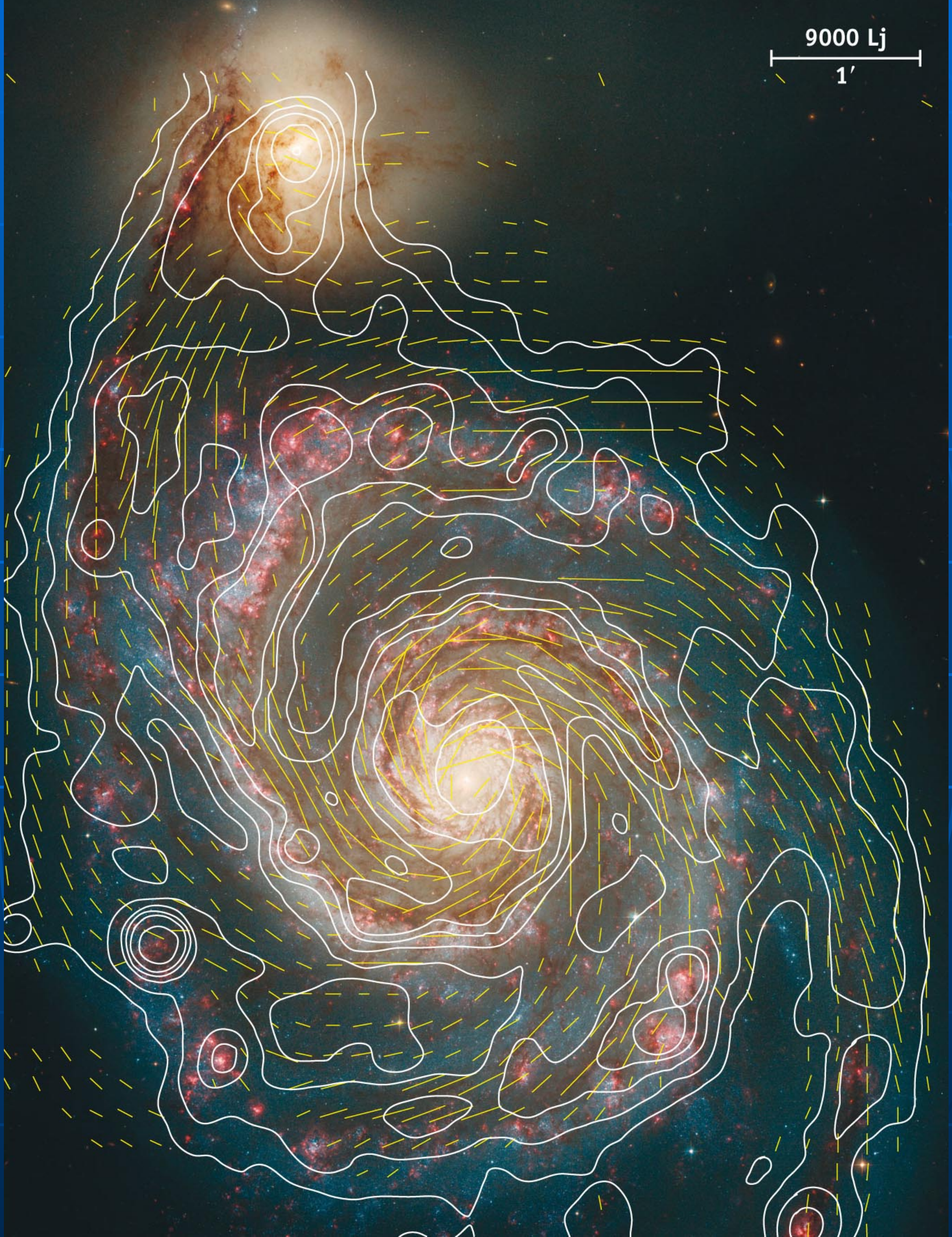
Regular field   Anisotropic field

Both give rise to polarized emission

M51

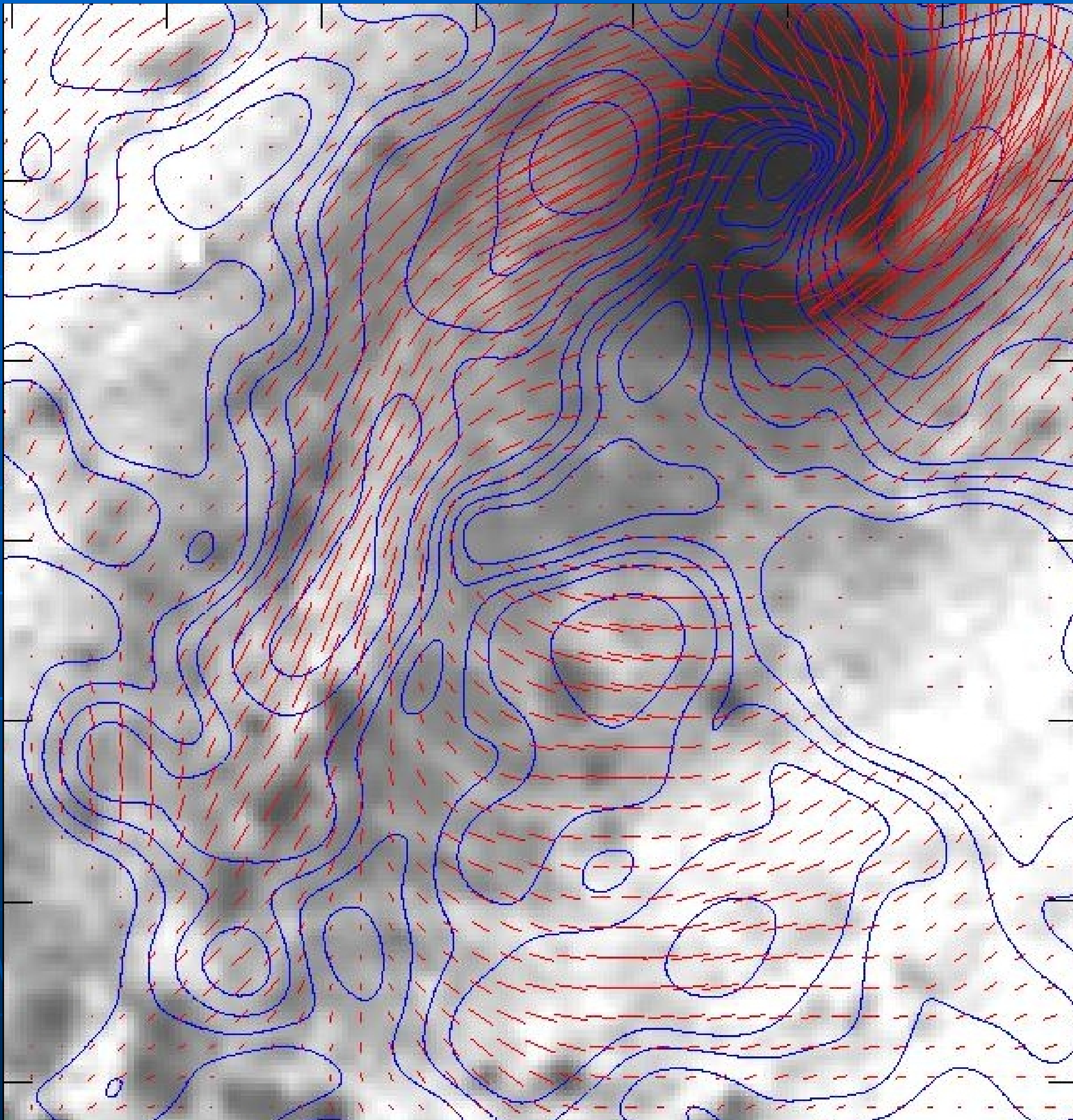
(Fletcher et al. 2007)

Spiral arms:
Anisotropic
fields due to
compressing
gas flows
+
regular
dynamo
fields



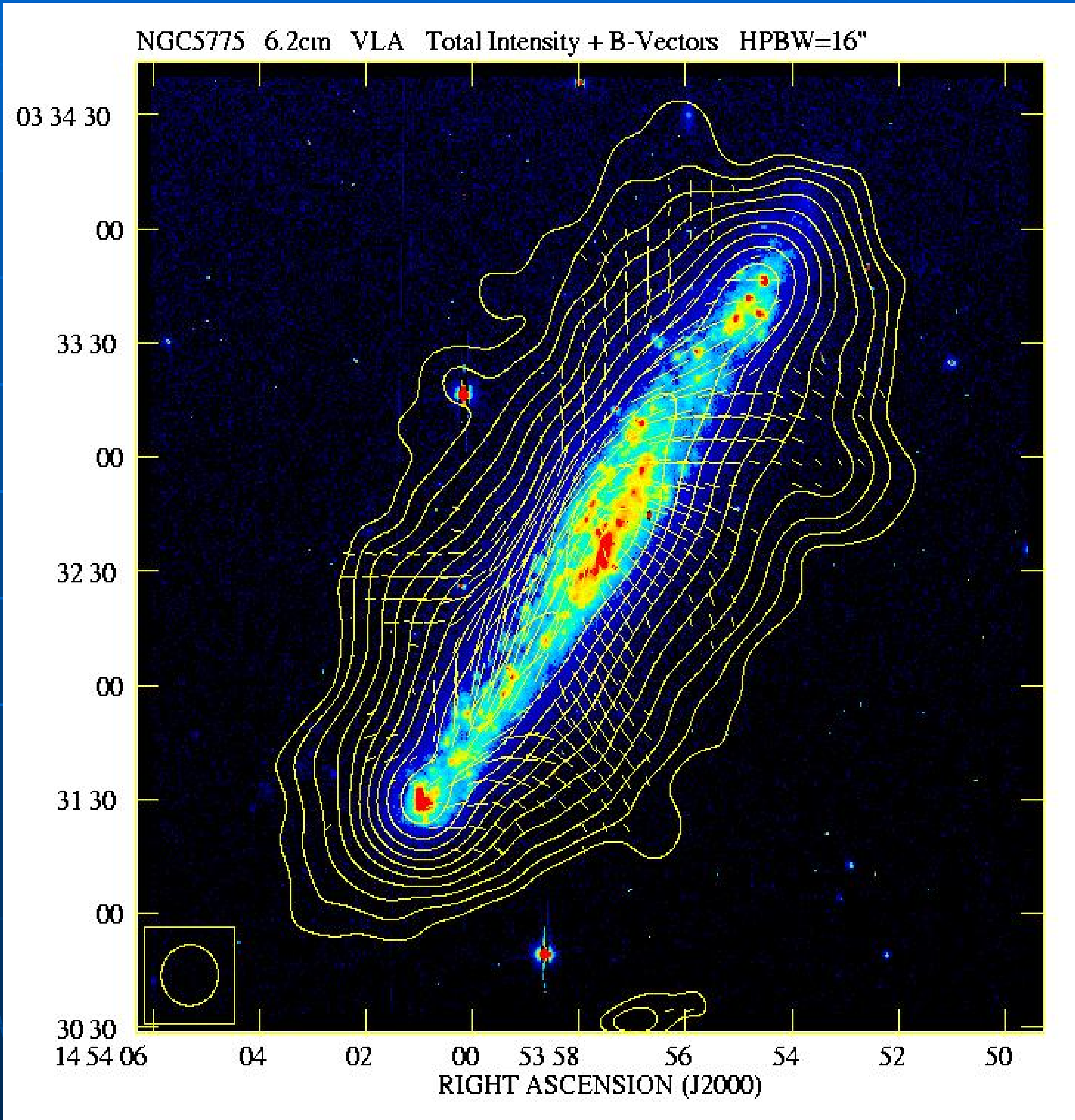
NGC 1097
(Beck et al. 2005)

Bars:
Anisotropic
fields
due to
shearing
gas flows

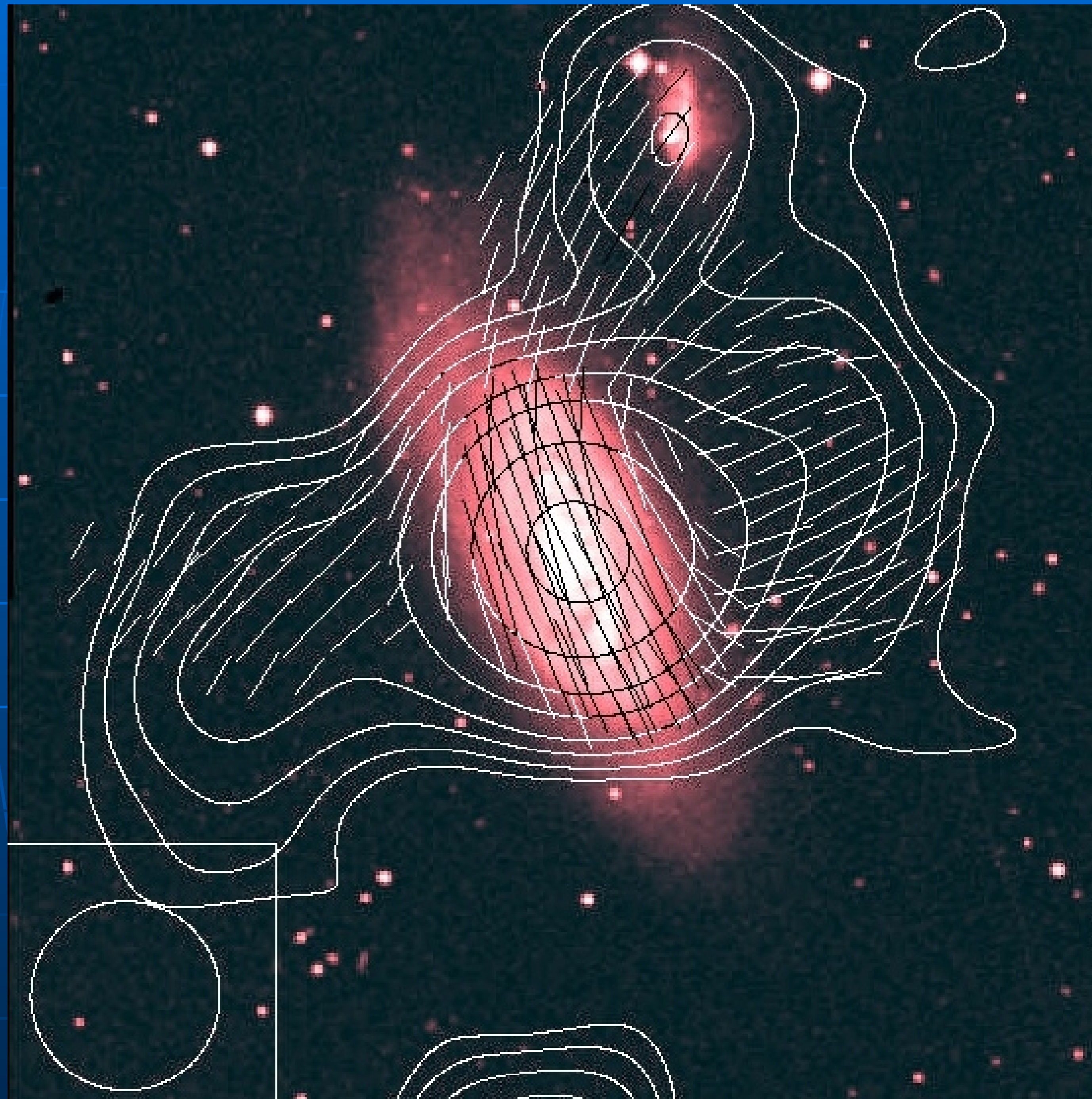


NGC 5775
(Tüllmann et al. 2001)

Halos:
Anisotropic
X-shaped
field lines
due to
shearing
gas flows



NGC 4569
6cm total+pol. intensity
(Chyzy et al. 2006)

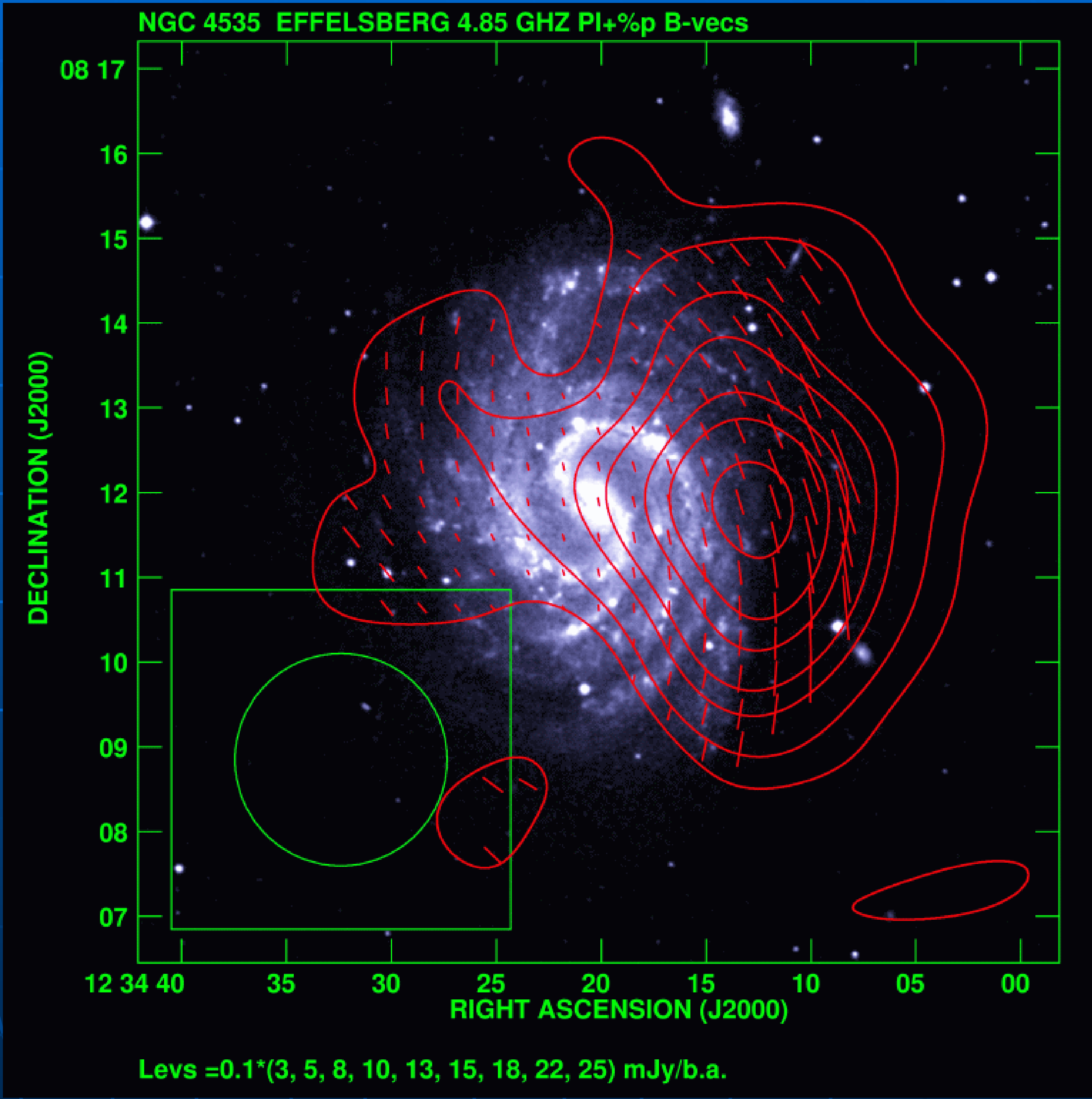


Polarization keeps memory of past interactions

NGC 4535

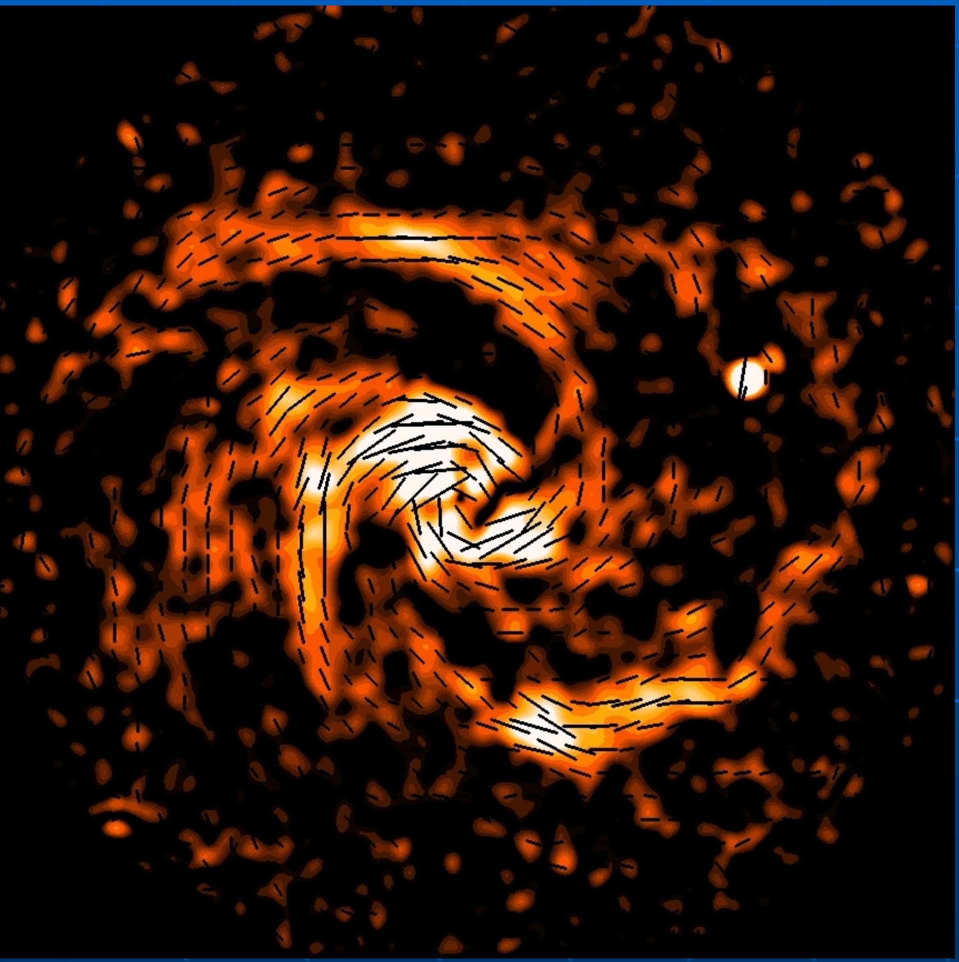
6cm polarized intensity

(Wezgowiec et al. 2007)

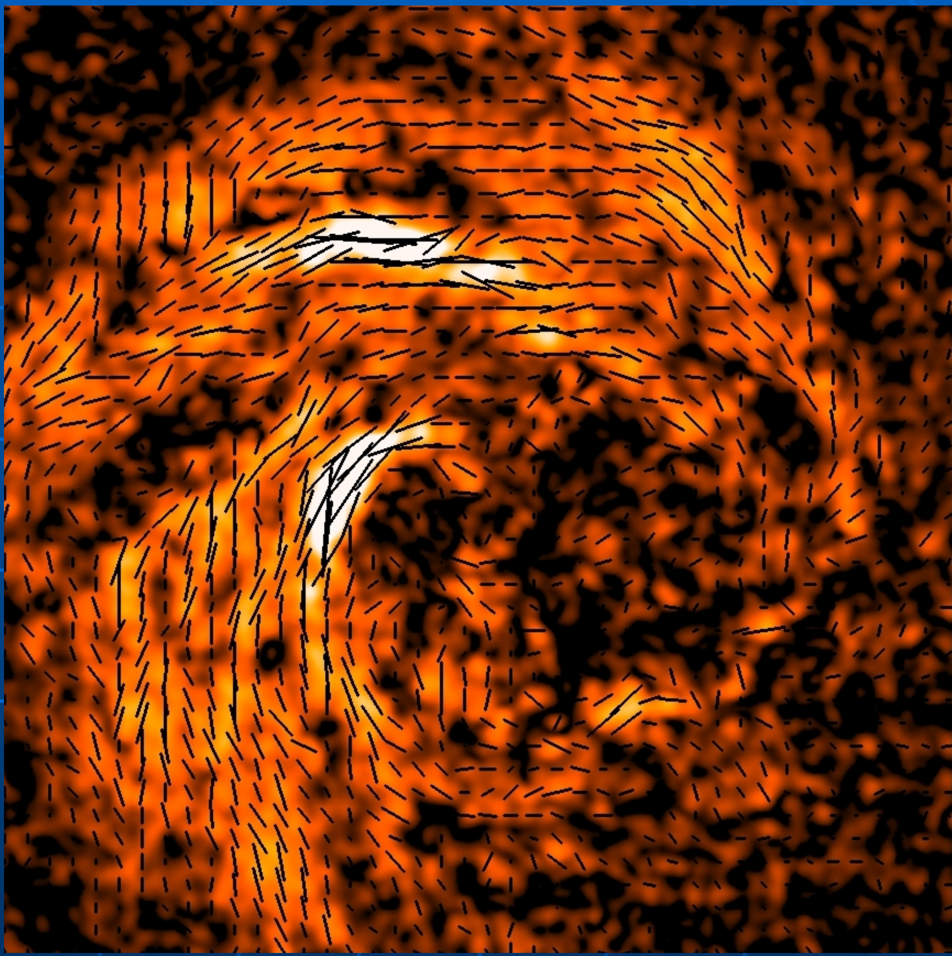


Polarization measures strength and direction of ram pressure

NGC6946 PI 6 cm



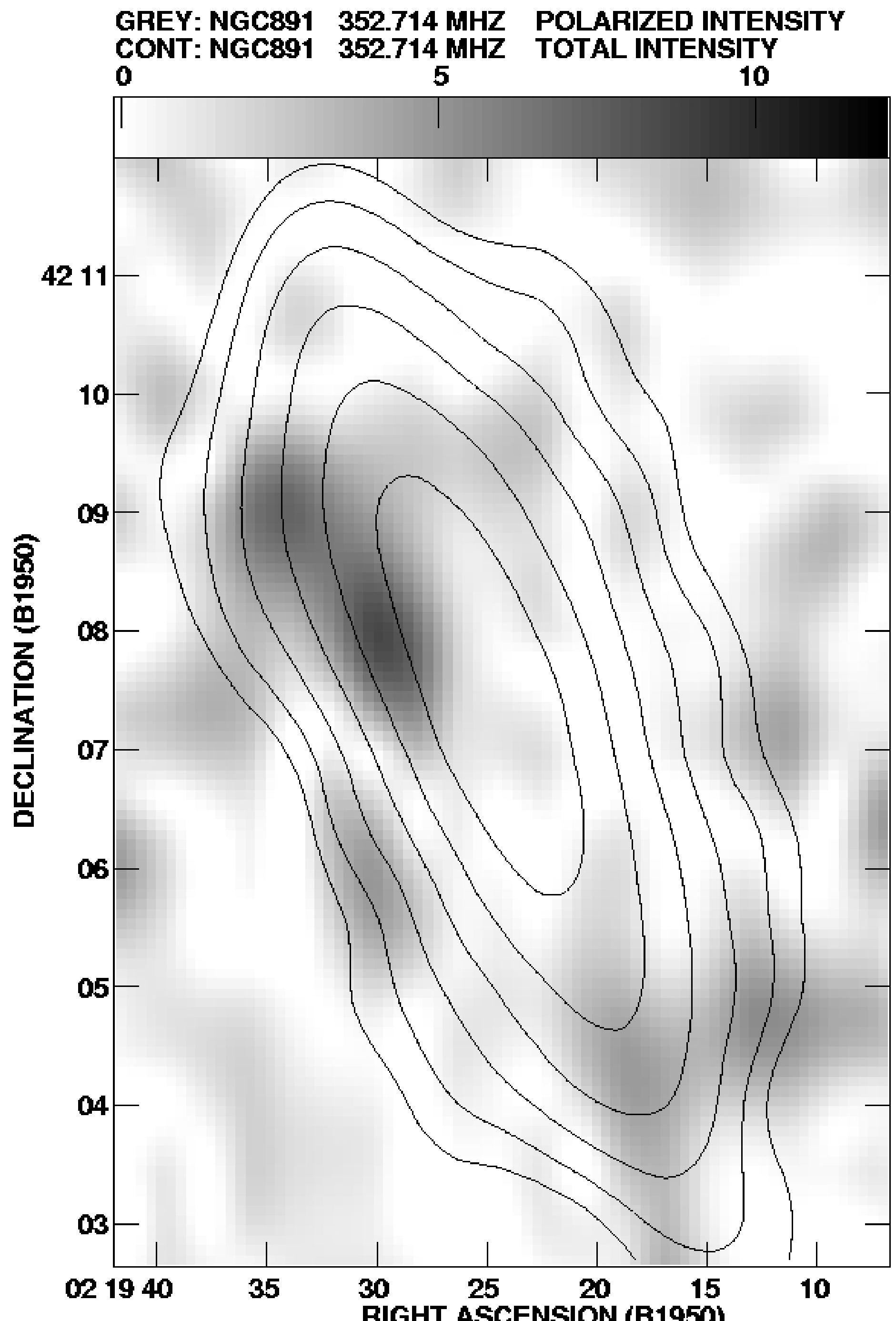
NGC6946 PI 20 cm



Strong Faraday depolarization

NGC 891

total + pol. intensity
WSRT 353 MHz
(de Bruyn et al.)



Observation of diffuse polarized emission with LOFAR

LOFAR

- Reduce Faraday depolarization:
  Use high spectral resolution & apply *RM Synthesis*

- Reduce beam depolarization:
  Observe with high spatial resolution
  (long baselines needed)

- Understand polarization calibration and
  Faraday rotation in the ionosphere

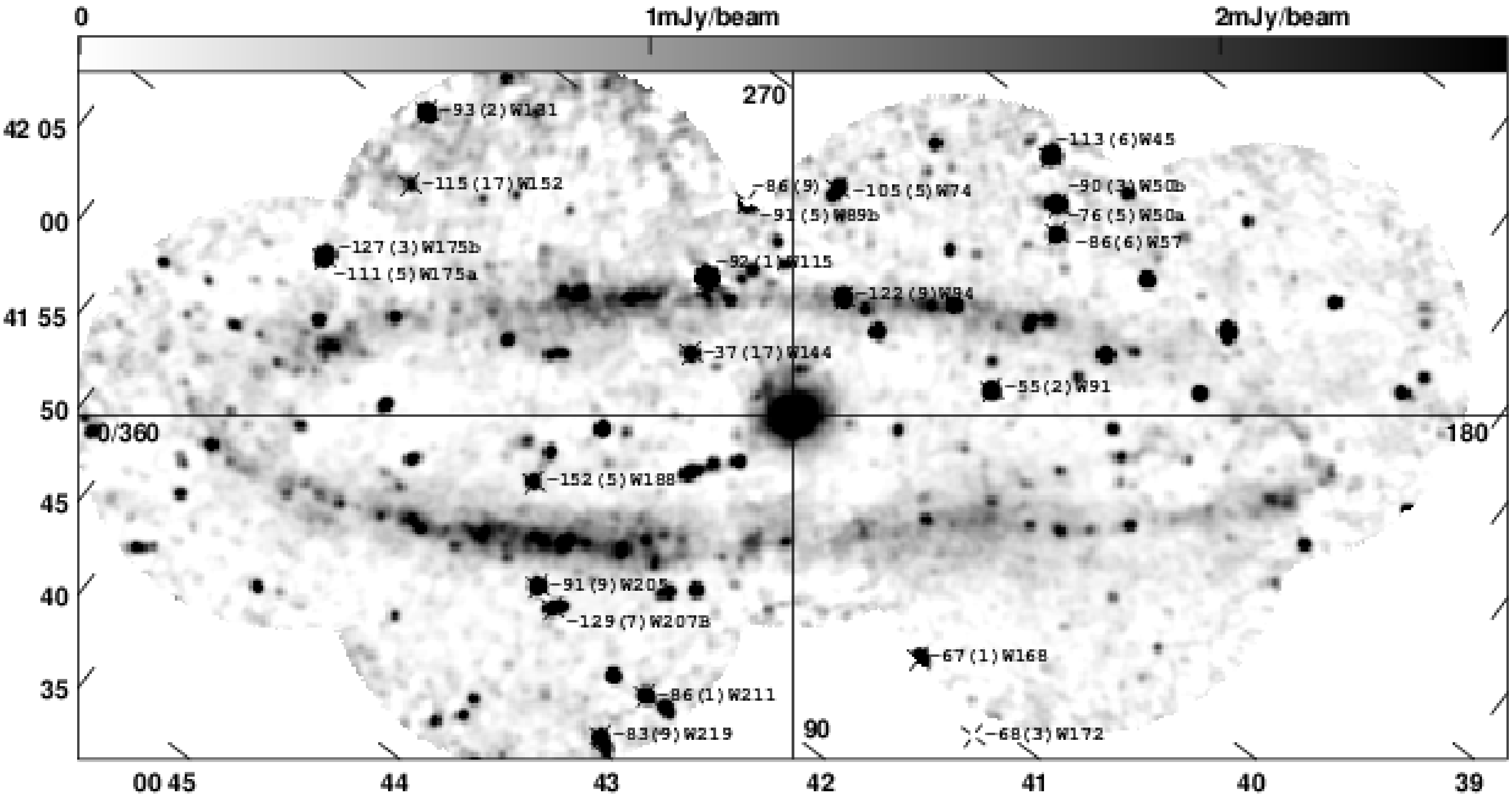
Faraday rotation

$\Delta\chi = 0.81(\text{rad})\ \lambda(\text{m})^2 \int n_e(\text{cm}^{-3})\ B_{reg\parallel}(\mu\text{G})\ dl(\text{pc})$

$= \textbf{RM}\ \lambda(\text{m})^2$

RMs towards polarized background sources (radio galaxies and pulsars) allow to detect thinner ionized gas and weaker magnetic fields than emission processes.

RMs through galaxies



RMs of 21 polarized sources shining through M31

Han et al. 1998

LOFAR RM surveys

LOFAR is very sensitive in measuring very low Faraday rotation measures of and hence can detect weak magnetic fields:

- Galaxy halos, clusters, relics:
  $n_e=10^{-3}$ cm^{-3}, $B_{||}$ =1 μG, L=1 kpc: RM~1 rad m^{-2}
- Intergalactic magnetic fields:
  $n_e=10^{-3}$ cm^{-3}, $B_{||}$ =0.1 μG, L=1 kpc: RM~0.1 rad m^{-2}

Faraday rotation angles

|RM| =		10	1	0.1 rad m^{-2}
1400 MHz	$\Delta\chi$ =	26°	3°	0.3°
200 MHz	$\Delta\chi$ =	1290°	129°	13°
120 MHz	$\Delta\chi$ =	3580°	358°	36°

- *Internal* rotation beyond 90° causes depolarization and requires narrow-band spectro-polarimetry
- *External* rotation beyond 180° needs multiband polarimetry

LOFAR RM surveys

Planned LOFAR all-sky continuum surveys:

- 15, 30, 60, 120 MHz (all sky)
- 200 MHz (selected regions)

Proposed Faraday rotation surveys:

- 60, 120 MHz (all sky, piggyback, needs full polarization calibration)
- 50-240 MHz (very deep selected regions)

LOFAR deep fields (diffuse pol and RM)

Selected objects:

- Galactic objects
- Dwarf galaxies
- Non-active elliptical galaxies
- Galactic halos
- Galaxy interactions
- Connections galaxies – intergalactic medium
- Galaxy clusters and relics
- Search for intergalactic magnetic fields

- ≈ 200h observation time per field,
  rms noise: ≈ 2 μJy at 200 MHz,
  below confusion in total intensity

Proposed International
Key Science Project :

Observing Cosmic Magnetism with LOFAR

Participants:
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+ UK, Poland, … more collaborators welcome !